TUNING OF COMPONENT CHARACTERISTICS MAPS IN OFF DESIGN SIMULATION OF GAS TURBINES

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Abstract: A reliable simulation model is an essential component of health monitoring system for gas turbine engines. Hence a thermodynamic simulation model of a twin spool gas turbine engine is being developed for use in an engine health monitoring (EHM) system. This model is based on mass and energy conservation principles across each component of the gas turbine engine. The model is being developed with limited design point information and measured gas path parameters available from the test bed. Both on-design and off-design models are being developed in Matlab® programming environment. Component characteristics maps available in the open literature are being scaled and used in the off design simulation. The scaling parameters used in the maps are tuned to improve the agreement between simulation model and data collected from engine test bed. Both tuned and untuned results of the simulation along with their respective errors are presented. The scheme to incorporate the model in the physics based health monitoring module is also briefly presented.

Keywords: Simulation, Engine health monitoring, Turbojet engine, Map scaling, Tuning.

1. INTRODUCTION

Engine health monitoring system (EHM), especially for legacy aircraft engines; contribute towards increasing reliability and decreasing the maintenance/overhaul cost of the engines. They collect sensor data from the engine continuously and identify the gradual shifts in the engine performance parameters that occur due to routine wear and tear and also the rapid deviations from the nominal values that occur due to failure of components such as bearings, labyrinth seals, nozzle actuators etc. Once failure or impending failure of a component is identified by the EHM module, it is communicated to the maintenance crew. The crew is then able to be prepared and take appropriate remedial action (like pre-ordering required components). Once a reliable EHM module is in place, the maintenance can be shifted from “schedule based’ maintenance to “requirement based” maintenance. This reduces the time the aircraft is grounded and also reduces the overhauls in which there was “No-fault-found” in the engine.

Such a twin spool-turbo jet engine health monitoring (EHM) module is currently being developed at Propulsion Division, CSIR-National Aerospace Laboratories for a legacy engine. This module is proposed to be installed on a trial basis at a ground level engine test bed facility. Both physics based and data based approach are being pursued in the development of this EHM module.

In the data based approach, the primary purpose of simulation model is to provide data for training of data driven models. Initially, the simulation modules provide sensor data sets (Healthy data) corresponding to the engine in its healthy condition to the data based models so that they can be trained on the ideal engine data. It is too expensive and sometimes not possible to inject faults in the actual engine in order to generate sensor data corresponding to engine that has faulty components. Hence these component faults are then injected into the simulation model to generate sensor data (un-healthy data) and the data based modules are then trained to identify the possible faults in the engine given the sensor data. The data models can then be ported on to the engine wherein they continuously monitor the gas path measurements and identify possible component degradation and faults, if any. The simulation model used in the generation of sensor data is presented in this paper.

In physics based approach, the operating condition and input parameters to the engine are also given as input to the simulation model. The preprocessed sensor measurements from the engine and the simulation model outputs are then compared and the residues are analyzed by the fault identification algorithms to obtain the current status of the engine's health. The scheme of this EHM module is shown in Figure 1.

Thus it is evident that the simulation model performs an important role in both approaches of EHM module development. However, in the absence of design information and component characteristic maps of the components, development of the model requires many assumptions and scaling of other engine’s maps. To a great extent, it is the validity of these assumptions and scaling of the maps that determine the agreement between simulation and experimental data.

Several thermodynamic simulation models have been developed in the past for gas turbine engines. One of the early reports of AGARD[1] describes the problems and few of the approaches in simulation of the gas turbines. The techniques and importance of off-design performance analysis for users and manufacturers has been pointed out in several researches[2]. The impact of loads on the running of gas turbines while considering inter-cooling and recuperation has also been presented[3]. A thermodynamic simulation program used in design, capable of generating thermodynamic cycles that satisfy the performance requirement at multiple points has been presented[4].

Few other prominent simulation gas turbine models have been briefly described by papers on model development[5,6]. Commercial software packages are also available for carrying out on-design, of-design and transient analysis. The user guide[7,8] for these software provide few insights into the working of the modeling program. In spite of the availability of the commercial software packages, the need for an in-house code for the thermodynamic analysis arises due to following reasons:

- The need to understand the component matching process in cycle analysis
- Tight integration required between sensor validation routines and simulation model.
- Data transfer requirement between simulation model and the neural network based tuning, fault identification and fault isolation routines.

This paper presents a simple model tuning approach that improves the better agreement between experiment and simulation. The development of the simulation model matching algorithm is presented in subsequent sections. Later model tuning and the simulation results before and after tuning are compared with test bed data.

2. COMPONENT MODEL AND MATCHING OF COMPONENTS

The EHM module development activities presented here are being done for a "**target engine**", which is a large twin spool, straight flow, turbojet engine. It has a continuously variable exit area convergent nozzle. The engine primarily is controlled through the power lever, whose angle is called as power lever angle (PLA). The LP spool RPM and exit area of the nozzle are functions of the PLA.

2.1 Component model

The main output of the thermodynamic simulation model is to predict the temperatures and pressures of the gas at each of the station along the gas path of the engine. In order to increase the accuracy, high fidelity models such as the one presented here, also account for varying gas compositions and effect of temperature on specific heats. The enthalpy of the working fluid is tracked from station to station to obtain the corresponding temperatures to the pressures. The equations describing the enthalpy based formulations for modeling the components like compressor and turbines have been presented[9]and implemented[6] in many previous works on the subject.

2.2 Matching of components

The matching algorithm for the twin spool using gradient based techniques is presented here in detail.

Once the component models have been developed, they are linked together in their logical sequence to form a complete on-design engine simulation model. Once required inputs such as design pressure ratio, efficiencies of compressors turbines and spools are given to the on design model, the design point simulation of the engine can be carried out. The main outputs of design point simulation will be

- Corrected RPM of turbo-machinery components.
- Design point exit area of the nozzle.
- Thrust and SFC of the engine.
- Major gas path parameters along the engine.

Once on-design simulations have been carried out, off design simulations can be proceeded with design point parameters as reference. The characteristics such as efficiency and pressure ratio of the turbo-machinery components at their off design states are given by their respective performance maps. Since the original component (performance) maps are not available for many legacy engines, available component maps of other engines have to be scaled to the design point of the target engine. Two common map scaling methods have been compared for their merits in a previous study[6]. The component models are supplied with their respective scaled characteristic maps and to start component matching. The matching procedure in this work was done in the following sequence.

HP spool RPM:

The corrected RPM of the hp spool is obtained from the requirement that the HP compressor must ingest the mass flow supplied by the LP compressor. Hence in the corrected mass flow map of the HP compressor, a reverse lookup is performed using the LP compressor exit corrected mass flow (which is same as HP compressor inlet corrected mass flow for no bleed air taken from LPC exit) and guessed HP beta.

HP beta(β_{hpc}), LP beta(β_{lpc}) and Main burner fuel flow (W_f):

These three are the variables that form the guess vector that uniquely identify the operating point of a twin spool jet engine for the given 3 constraints. The 3 constraints are described below.

Corrected mass flow($\dot{m}_c$) match at HP turbine(ε_{mc}^{HPT}=0):

Matching between combustor outlet ($\dot{m}_c$) and the ($\dot{m}_c$) obtained from satisfying the work balance between HP turbine (HPT) and HP compressor (HPC).

$\dot{m}_c$match at LP turbine(ε_{mc}^{LPT}=0):

Matching between HP turbine outlet ($\dot{m}_c$) and the ($\dot{m}_c$) obtained from satisfying the work balance between LP turbine (LPT) and LP compressor (LPC).

$\dot{m}_c$ Match at Nozzle: (ε_{mc}^{nozz}=0)

Matching between LP turbine outlet ($\dot{m}_c$) and the ($\dot{m}_c$) obtained from satisfying the mass flow requirement for the given static pressure, temperature and exit area of the nozzle.

A flow chart depicting a similar scheme has been presented in reference[9]. In turbo-shaft engines, the operating point of the cycle can be shifted by changing the torque requirement from the shaft at each RPM. Analogously the turbojet's operating point can be shifted by varying the nozzle area at each RPM. Thus, though input from the user to the simulation model is only PLA (in addition to ambient pressure and temperature), the input given to the simulation model is both the required RPM and exit area of the nozzle (as a function of to PLA).

A simple Jacobian based iterative scheme has been used to find out the operating point in terms of the guess vector $\begin{bmatrix}\beta_{lpc}\\ \beta_{hpc}\\ W_f\end{bmatrix}$ such that the error vector $\begin{bmatrix}\varepsilon_{mc}^{HPT}\\ \varepsilon_{mc}^{LPT}\\ \varepsilon_{mc}^{nozz}\end{bmatrix} = 0$. It is convenient to proceed through the off-design simulation from higher RPM to lower RPM as the design point vector can be used as an initial guess vector for the next lower RPM. Successive lower RPM can use the previous higher RPM's converged vector as the guess vector. Thus with the guess vectors, error vectors can be evaluated and the iterations can be taken forward in the conventional way.

$$\begin{bmatrix}\frac{\partial\varepsilon_{mc}^{HPT}}{\partial\beta_{lpc}} & \frac{\partial\varepsilon_{mc}^{HPT}}{\partial\beta_{hpc}} & \frac{\partial\varepsilon_{mc}^{HPT}}{\partial W_f}\\ \frac{\partial\varepsilon_{mc}^{LPT}}{\partial\beta_{lpc}} & \frac{\partial\varepsilon_{mc}^{LPT}}{\partial\beta_{hpc}} & \frac{\partial\varepsilon_{mc}^{LPT}}{\partial W_f}\\ \frac{\partial\varepsilon_{mc}^{nozz}}{\partial\beta_{lpc}} & \frac{\partial\varepsilon_{mc}^{nozz}}{\partial\beta_{hpc}} & \frac{\partial\varepsilon_{mc}^{nozz}}{\partial W_f}\end{bmatrix}\begin{bmatrix}\Delta\beta_{lpc}\\ \Delta\beta_{hpc}\\ \Delta W_f\end{bmatrix} = \begin{bmatrix}\varepsilon_{mc}^{HPT}\\ \varepsilon_{mc}^{LPT}\\ \varepsilon_{mc}^{nozz}\end{bmatrix}_{\substack{error\\ at\ current\\ guess}}$$

Figure **2** shows the reduction in error and the convergence of guess vector from 98.8% N1 RPM to 97.7% N1 RPM. In this figure, the first row shows that the error values at HPT, LPT and nozzle decrease towards zero and the second row shows that the guess vector converges to a steady value. Once the iterative scheme has been established, the model can be taken from 100% RPM to 75% RPM in small steps.

3. TUNING OF THE MODEL

The scaling method based simple linear scaling is used in present work as it requires only one scale factor per map of each component. Since the available measurements from the engine are few, it is advantageous to use a scaling method that requires fewer inputs.

The independent variables that are being tuned are the design beta (β) values of the reference map. It is this map that is being scaled to the target engine's specifications. The scale factors used in scaling are a function of design values of the target engine and design values of the reference map. The design values of the target engine are fixed. But the design beta value of the compressor and turbine reference maps are usually chosen such that thermodynamic matching is possible using the scaled maps. In this work, the beta values of the reference maps are kept as independents and are varied within the bounds such that the objective function is minimized.

At the test bed, gas path parameters at HPC exit and LPT exit are only measured. The performance of the engine in terms the static pressures and total temperatures at these locations at off-design conditions has been plotted in Figure 3. In these figures, simulation model output and test bed measurement have been superimposed. The black cross marks indicate the experimental data points available at certain ratings of the engine. The blue curve is a polynomial fit to the experimental data points. Red circles indicate output of the simulation at regular intervals between 75% and 100% N1 RPM. The errors are mean absolute percentage errors ($AMPE, \varepsilon^{ampe}$) computed between the simulation model output (red circles) and the curve that has been fit to the experimental data (blue line).

The 4 errors are

- Error in static pressure at HPC exit (ε_{p2}^{ampe})
- Error in total temperature at HPC exit (ε_{t2}^{ampe})
- Error in static pressure at LPT exit (ε_{p4}^{ampe})
- Error in total temperature at LPT exit (ε_{t4}^{ampe})

Thus computed error vector is given as the objective function to a constrained non-linear optimization routine - *fmincon* of Matlab®. The vector's initial value and final converged value is given in Table 1 and difference between un-tuned and tuned results is given in Table 2.

Parameter	Initial Guess	Final value
β_{lpc}	0.9	0.9270
β_{hpc}	0.9	0.8730
β_{hpt}	0.75	0.7275
β_{lpt}	0.75	0.7275

Table 1 Independent Variables

Absolute Mean percentage error	Before Tuning	After Tuning
Compressor exit static pressure	6.3	5.5
Compressor exit total temperature	1.0	0.8
Turbine exit static pressure	6.9	6.4
Turbine exit total temperature	1.9	1.6

Table 2 Results of tuning

4. RESULTS

Results shown in Table 2 and the improvements shown between Figure **3** and Figure **4** indicate an improvement in accuracy of the simulation as a result of optimized selection of design value of the reference characteristic map. This implies that, when the design beta values are tuned and the maps scaled using them, the scaled maps represent the target engine's characteristics better.

Since the target engine has a control loop change over at 100% RPM of N1, there are multiple values of gas path parameters for the same N1 RPM value near 100% RPM. Hence the experimental data points are plotted only for RPM less than 97%. The curves that were fitted using data points less than 97% RPM were extrapolated to 100% RPM to obtain the estimated design point of the engine in terms of compressor and turbine delivery temperature and pressures. Since the engine is usually run at only specific ratings, bunching of the experimental data points is seen in these plots. The Y axis has been normalized between 0 and 1 in these plots for confidentiality reasons.

Though the pressures and temperatures at compressor and turbine exit agree within 6.5% of AMPE using the converged beta values, improvements need to be made. In the absence of design data, several assumptions such as spool power transmission efficiencies, turbine and compressor design isentropic efficiencies and duct pressure losses have been made. These assumptions need to be further tuned and the turbo machinery maps need to be modified to further reduce errors wrt test bed data.

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5. REFERENCES

1. Fottner, I. L. "Steady and transient performance prediction of gas turbine engines" (1992). doi:ISBN 92-835-0674-X

2. Ivanov, M.,"Mathematical Models of Gas Turbine Engines and their Components", (NATO, 1994).

3. Vishal Sethi , PhD thesis, "Advanced Performance Simulation of Gas Turbine Components and Fluid Thermodynamic Properties", (2008).

4. Schutte, J. S,"Simultaneous multi design point approach to gas turbine on design cycle analysis for aircraft engines" (2009).

5. Kapadi, S; Pashilkar, A. "Aero-Thermodynamic Modelfor Digital Simulationof TurbofanEngine", (2005).

6. Sankar, B., Shah, B., Thennavarajan, S. & Vanam, V. On Gas Turbine Simulation Model Development. Natl. Conf. Cond. Monit. (NCCM), Oct. 4-5, 2013 Bangalore 1–17 (2013).

7. Lucht, N., National, R. & Team, GSP 11 User manual.

8. Kurzke, J. GasTurb Details5. (2007).

9. Walsh, P. P. F. P . [Gas Turbine Performance],Blackwell Science, 2003, at <www.blackwellpublishing.com>

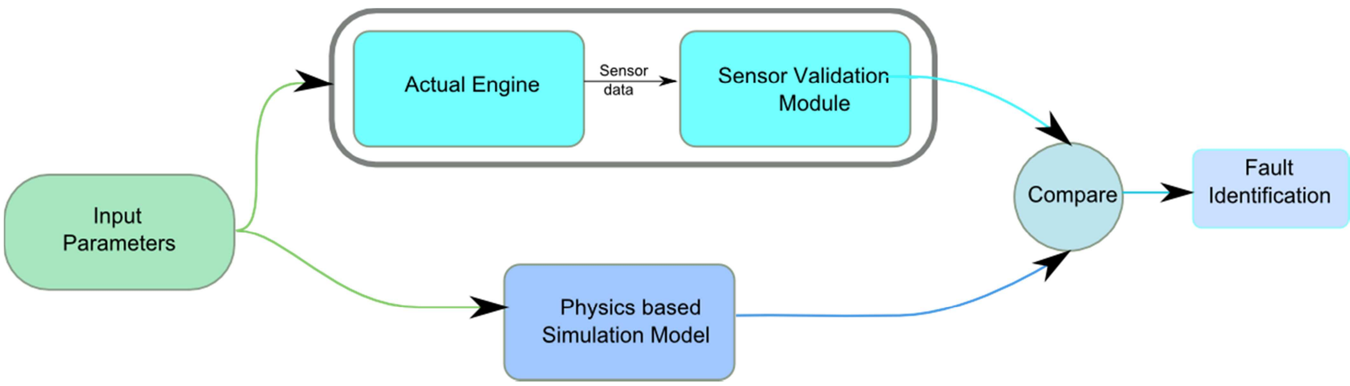

Figure 1 Physics based EHM scheme

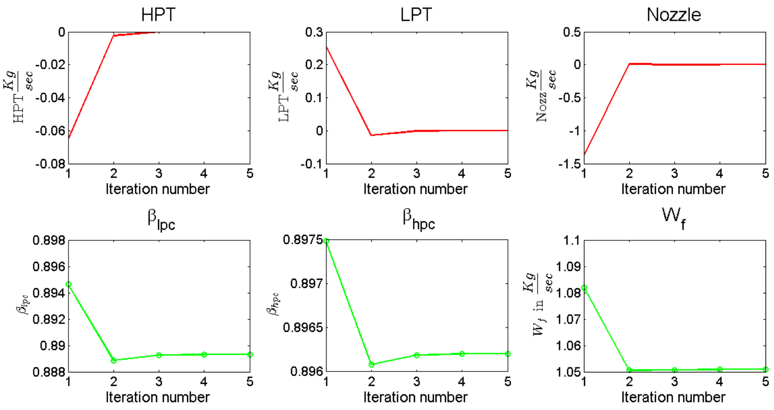

Figure 2 Reduction in error and convergence of guess vector while iterating from 98.8% to 97.7% of LP RPM.

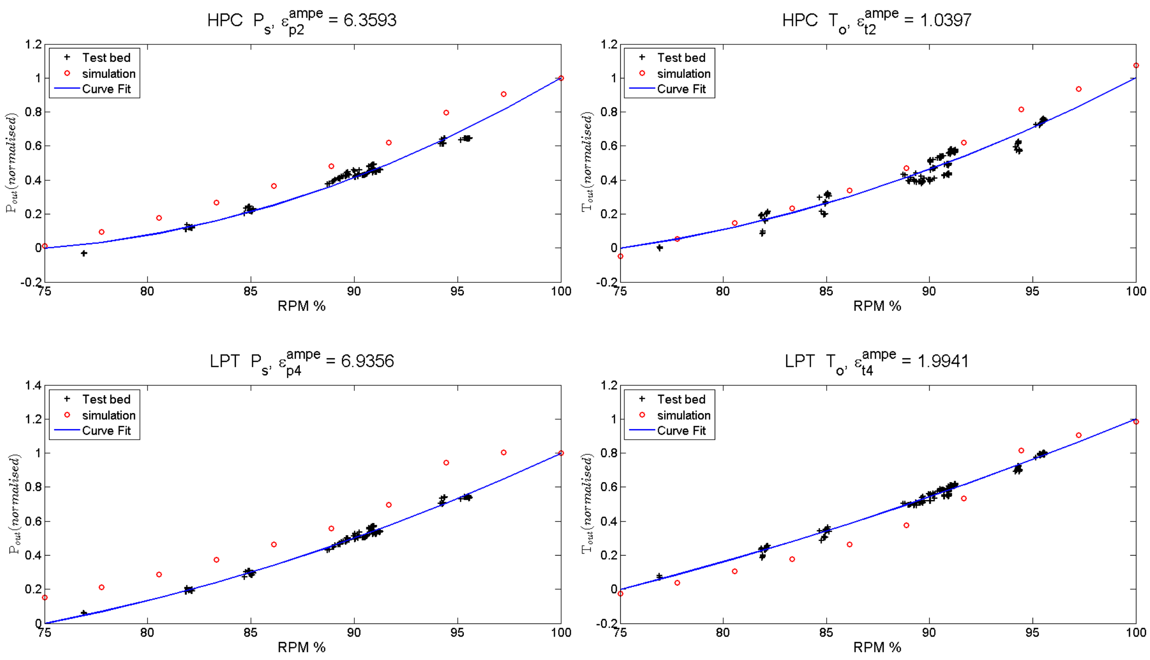

Figure 3 Off-design performance prediction, before tuning.

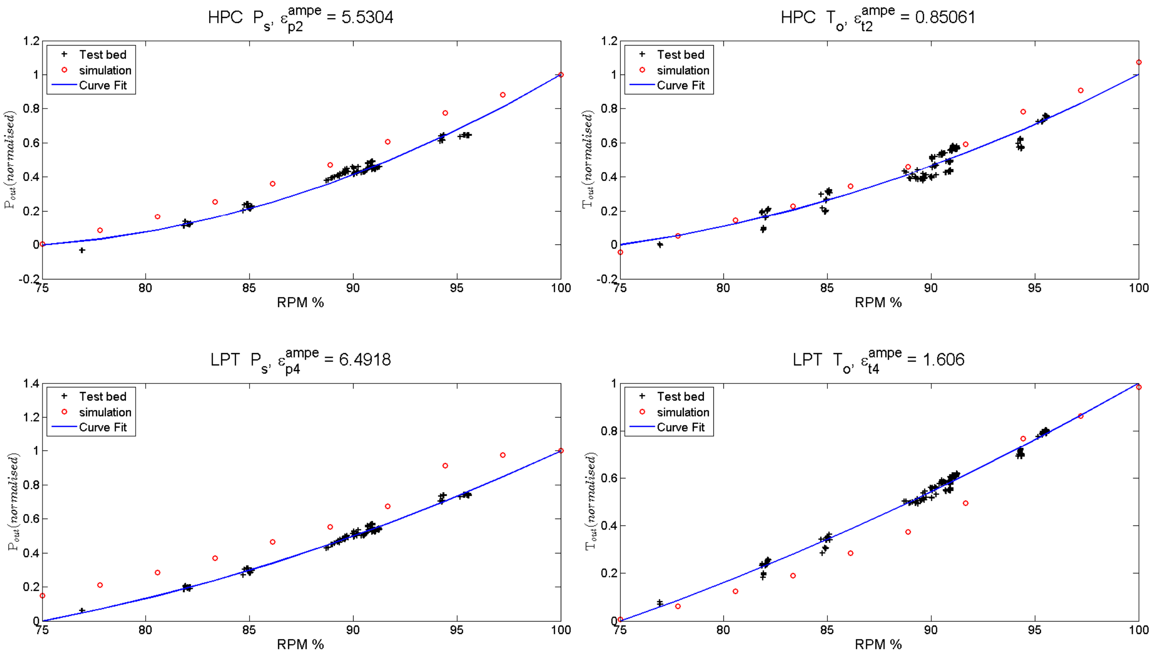

Figure 4 Off-design performance prediction, after tuning